Human/Hardware-in-the-Loop Testbed of Cargo Transfer Operations at Sea

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Outline

- Background
- Testbed Development and Integration
  - Software Architecture
  - Subsystem Modules
  - Integrated Virtual Environment
- Uses of the Testbed
  - Control System Performance
  - Engineering Design and Evaluation
- Summary & Discussion

Pendulation Control System Background

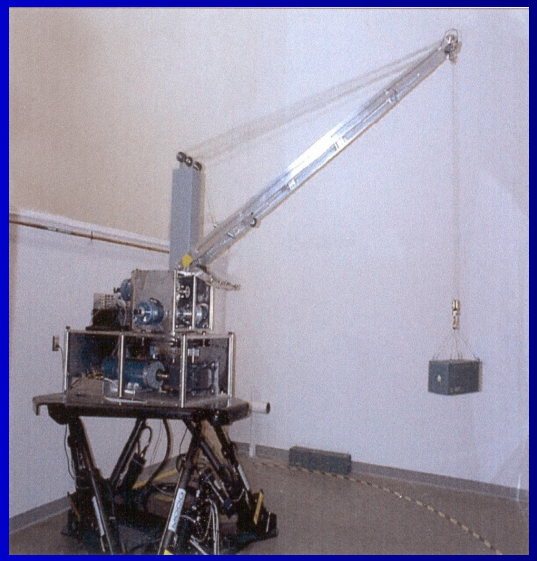
ONR funded an Advanced Technology Demonstration (ATD) of the Advanced Shipboard Crane Motion Control System (1999-2002)

- Demonstrated the feasibility of implementing a motion compensating control system on an existing crane
- Modern digital machinery controller installed to support computer interface (MacGREGOR CC2000)
- CC2000/Sandia National Lab algorithm combination = Pendulation Control System (PCS)

Technology successfully demonstrated pier-side. Pendulation controlled. At-sea testing would be needed to explore full capability of PCS.

Pendulation Control System Background

1/16th-scale crane model demonstrating motion compensating control algorithm developed by Sandia National Laboratory under ONR-funded ATD.



Pier-side testing of the Pendulation Control System on board the S.S. Flickertail State at Cheatham Annex in 2002.

The *S.S. Flickertail State*, while moored skin-to-skin to the *S.S. Cornhusker State*, transfers a container using the Pendulation Control System.

Further PCS Development & Technology Initiatives

- JLOTS 04 New Horizons indicated that LO/LO throughput needs to be improved even in calm sea conditions. Too much time spent in connecting to and positioning containers on deck.
- Investigate alternative payload motion sensing technologies.
- Develop twin-, quad-, and team-mode (coordinated multi-crane lift) operation with PCS to support full utilization of crane capabilities.
- Investigate enhanced Crane Operator Display for situational awareness and PCS status monitoring.

Testbed Project Objective

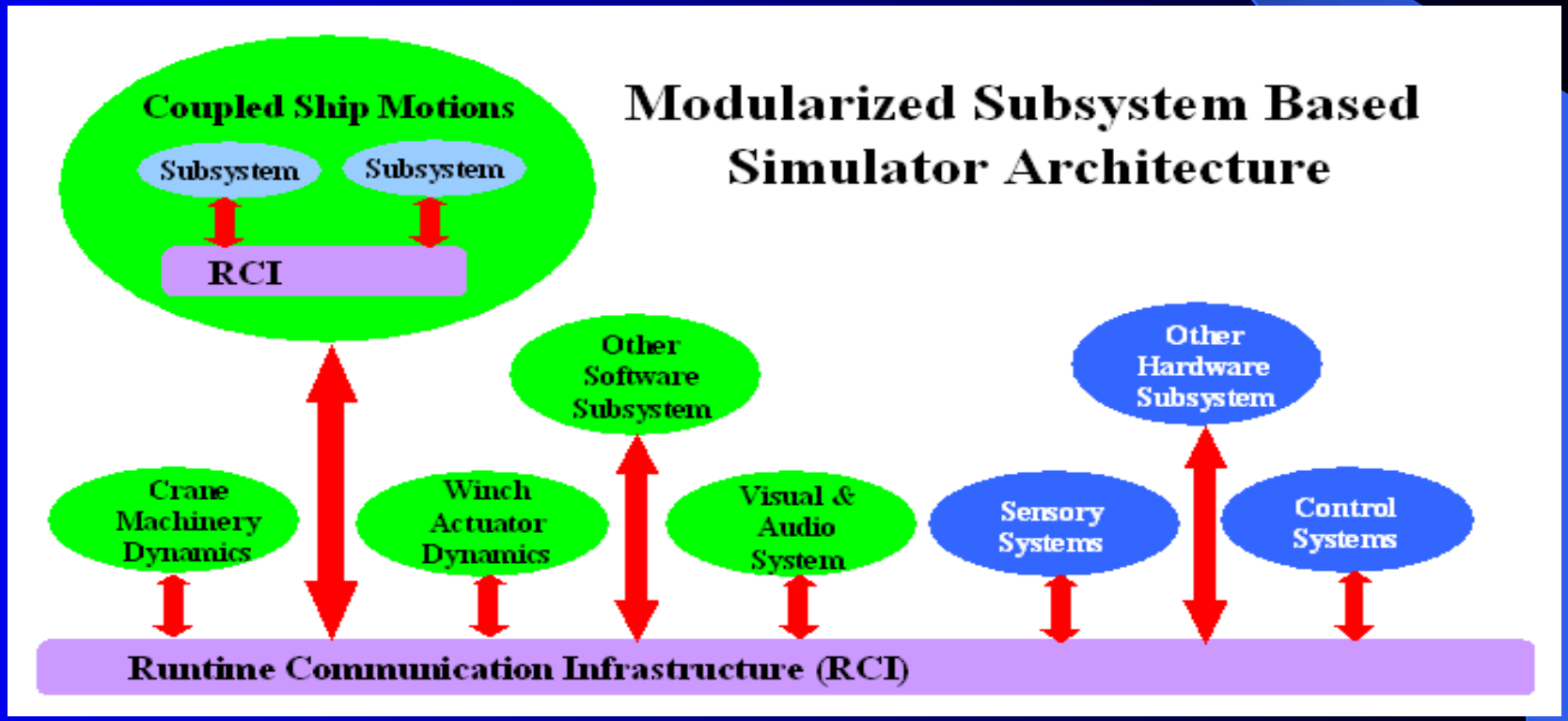
To build a physics-based, high fidelity testbed for engineering testing and evaluation of emerging concepts in cargo transfer operations at sea

Desired Capabilities -

- Hydrodynamics simulation of multiple vessels
- Ship-mounted crane machinery dynamics
- Advanced crane control systems
- Mooring lines and fenders
- Hardware-in-the-loop simulations
- Human-in-the-loop simulations

Software Architecture

- PC-based, real-time simulation system
- Software and hardware subsystem modules
- Open-architecture and object-oriented design



Crane Machinery Dynamics

- Hagglunds TG3637 pedestal crane in the *SS Flickertail State*
- Modeled as a rigid multibody system
- Pulled by hoisting, luffing, tagline, and liftline cables
- Slew motion and twin crane rotation

The Equations of Motion

- A set of differential-algebraic equations based on Lagrangian Mechanics
- Using an efficient O(n) formulation to achieve real-time computation performance
- Requires <10% CPU power of Intel Pentium 4

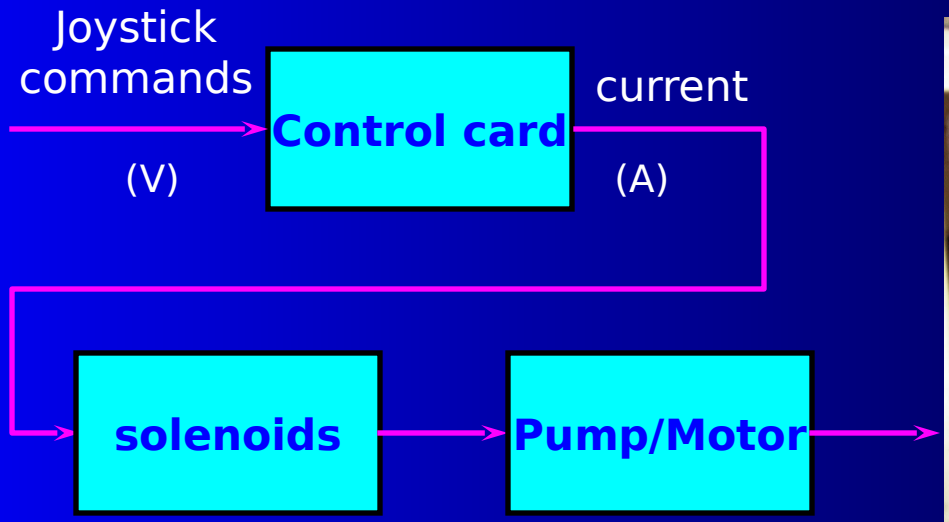
$$\ddot{\vec{u}} = C(\vec{q}, t) \bullet \dot{\vec{q}} + D(\vec{q})$$

$$M(\vec{q}, t; \vec{p}) \bullet \dot{\vec{u}} + \Phi^{T}_{,q}(\vec{q}, t; \vec{p}) \bullet \lambda = K(\vec{q}, \dot{\vec{q}}, t; \vec{p})$$

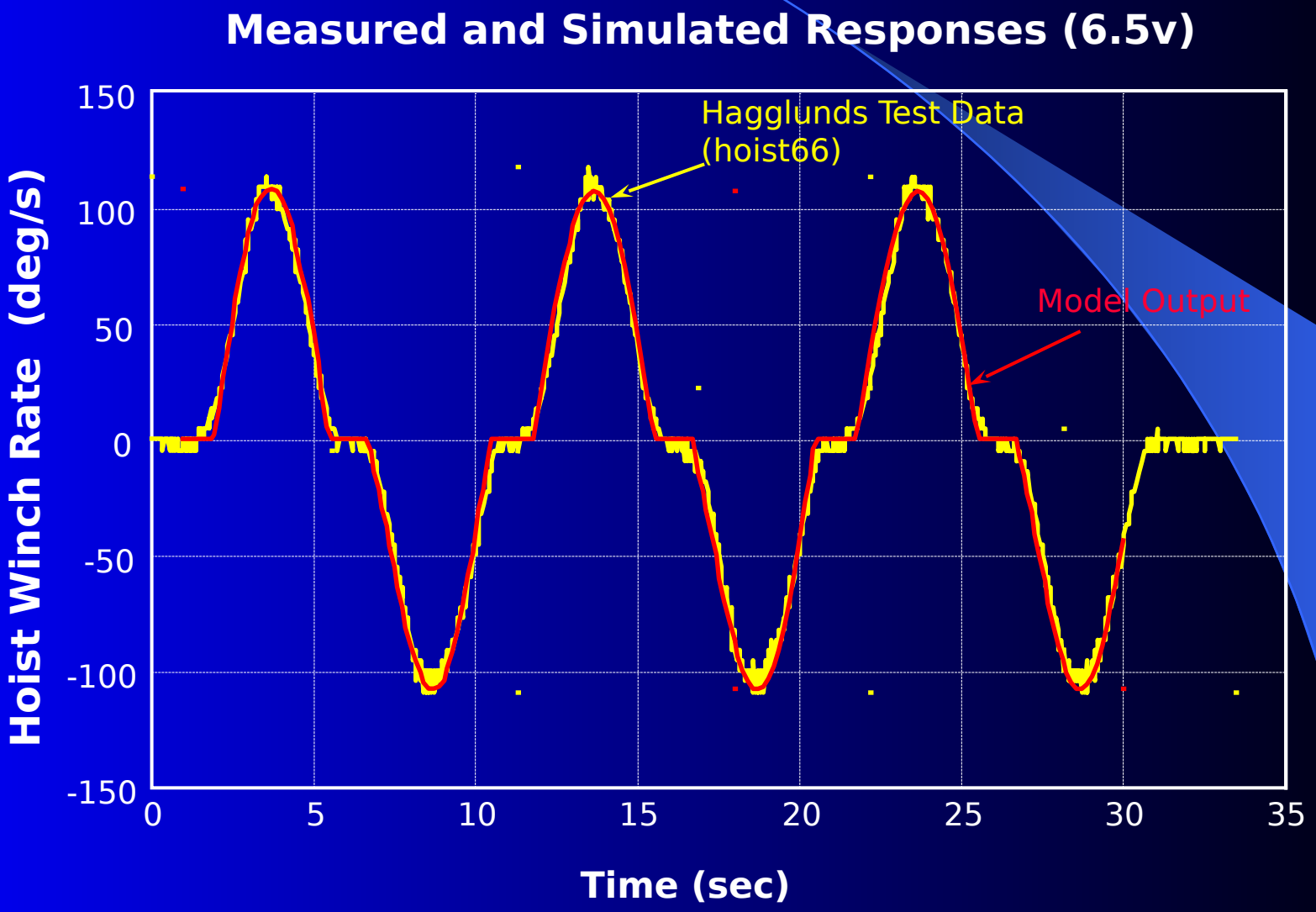
$$\Phi(\vec{q}, t; \vec{p}) = 0$$

Winch Actuator Dynamics

- Internal-state based, non-lumped drive system models to represent winch actuator dynamics
- Useful information for sensory feedback design
- Validated against field test data



Drive System Model Validation



Coupled Ship Motions

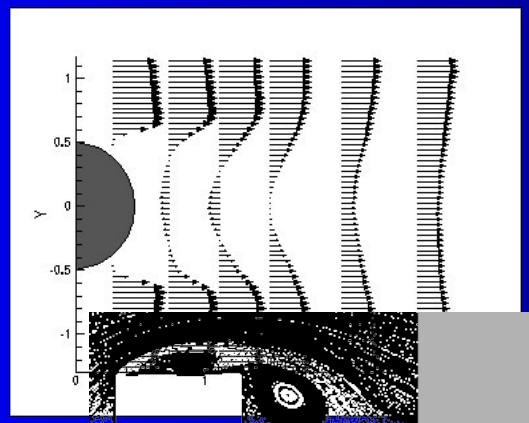
- Real-time computations in time-domain
- Multiple vessel configuration at very close proximity at slow speed of advance
- Coupled hydrodynamics

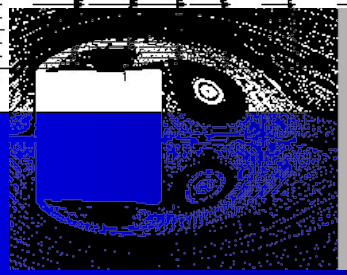
$$[A]\{\ddot{x}\} + \int_{-\infty}^{t} [K(t-\tau)]\{\dot{x}(\tau)\}\,d\tau + [C]\{x\}$$

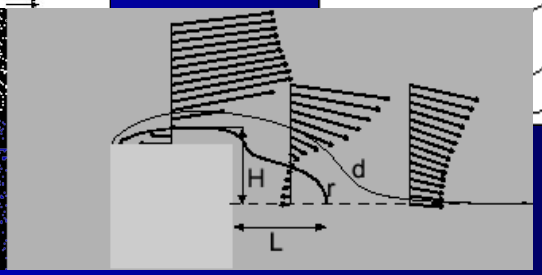
$$= \int_{-\infty}^{\infty} K_D(t-\tau,\beta)\zeta(\tau)d\tau + \{F_W\} + \{F_{others}\}$$

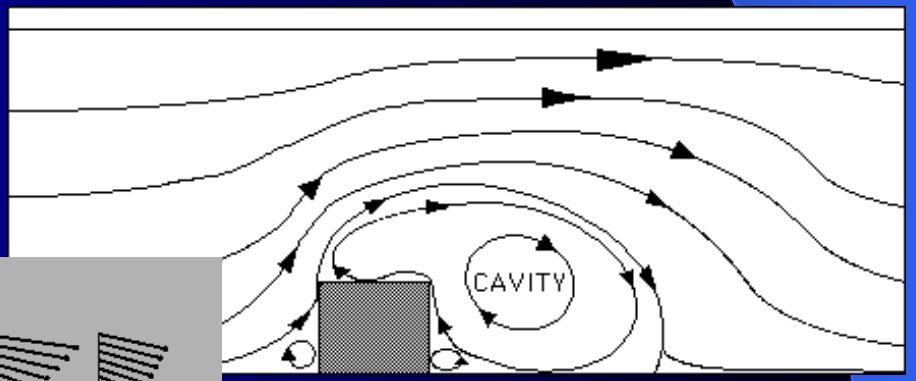
Time-Domain Interactions

- Other external forces include current, wind, wave-drift, mooring lines, fenders, anchor/chain, and viscous roll damping
- Specify one or two wave spectra simultaneously (Bretschneider, Ochi-Hubble, JONSWAP)



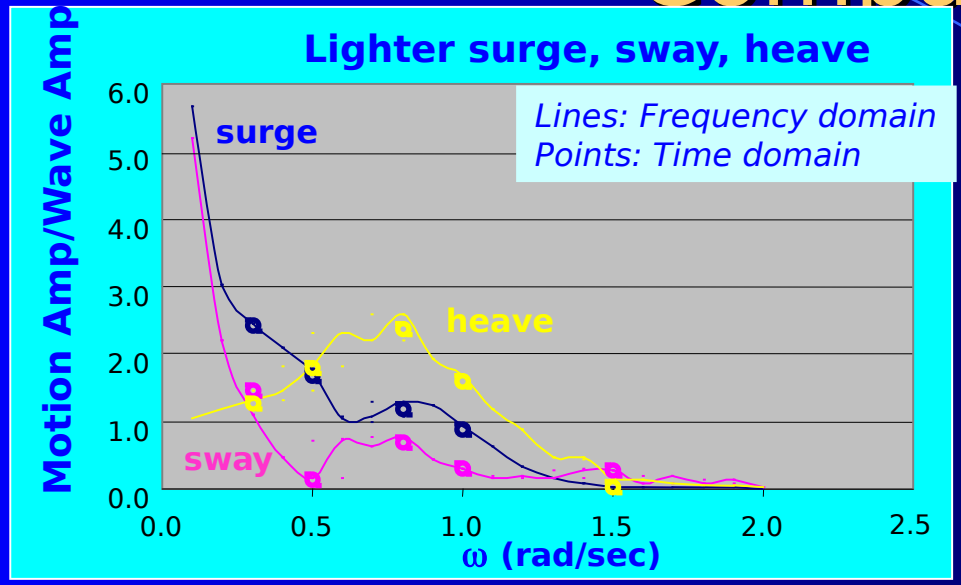


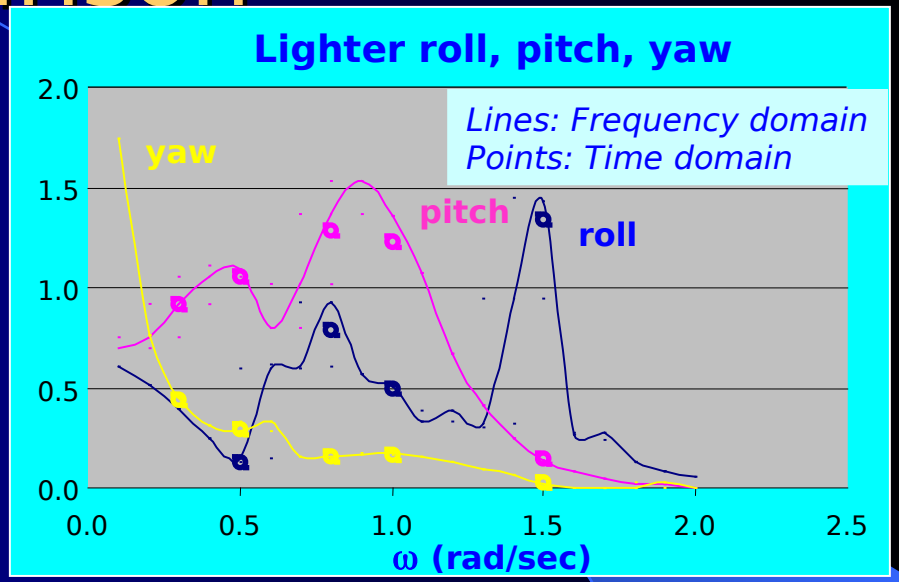


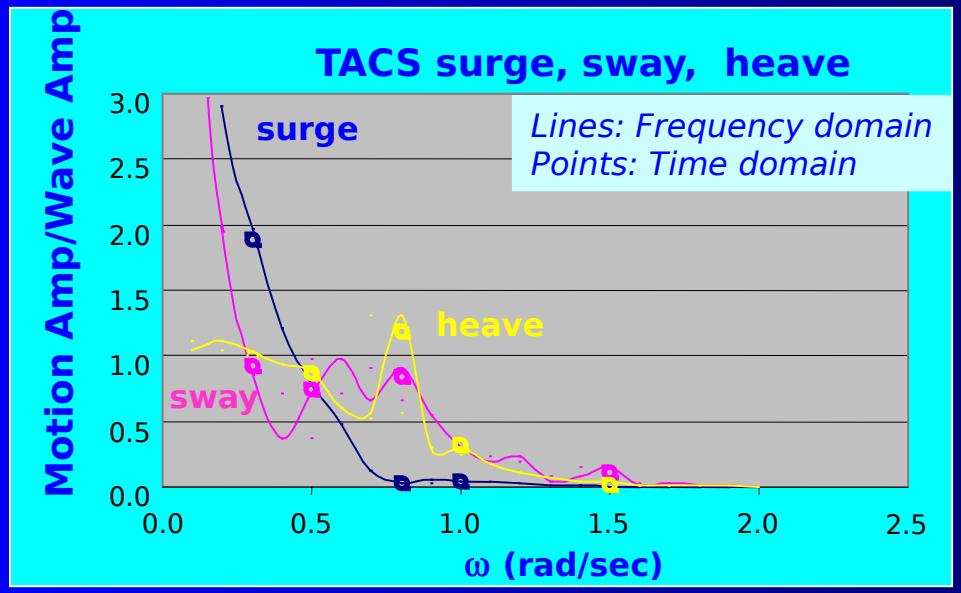


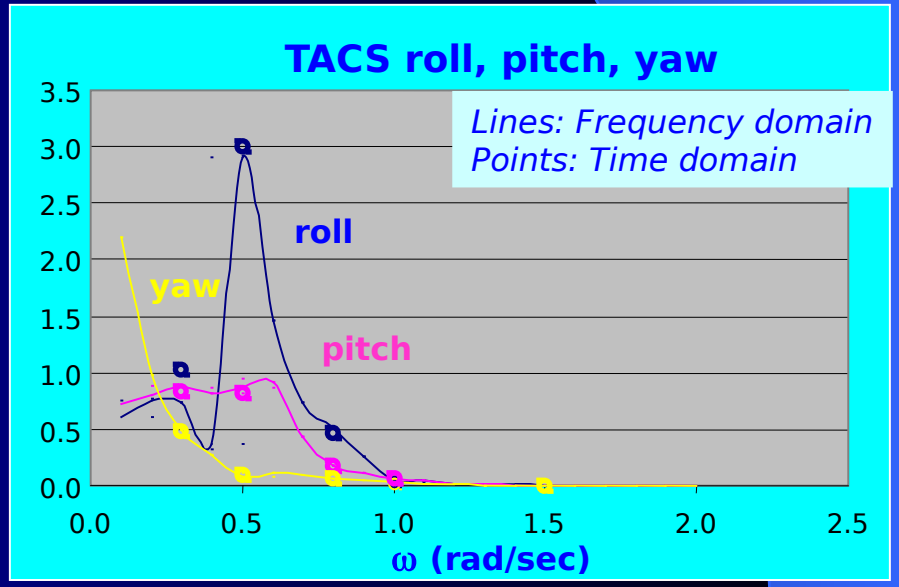
"shielding algorithm" based on theory of turbulent wa

Hydro Implementation Comparison



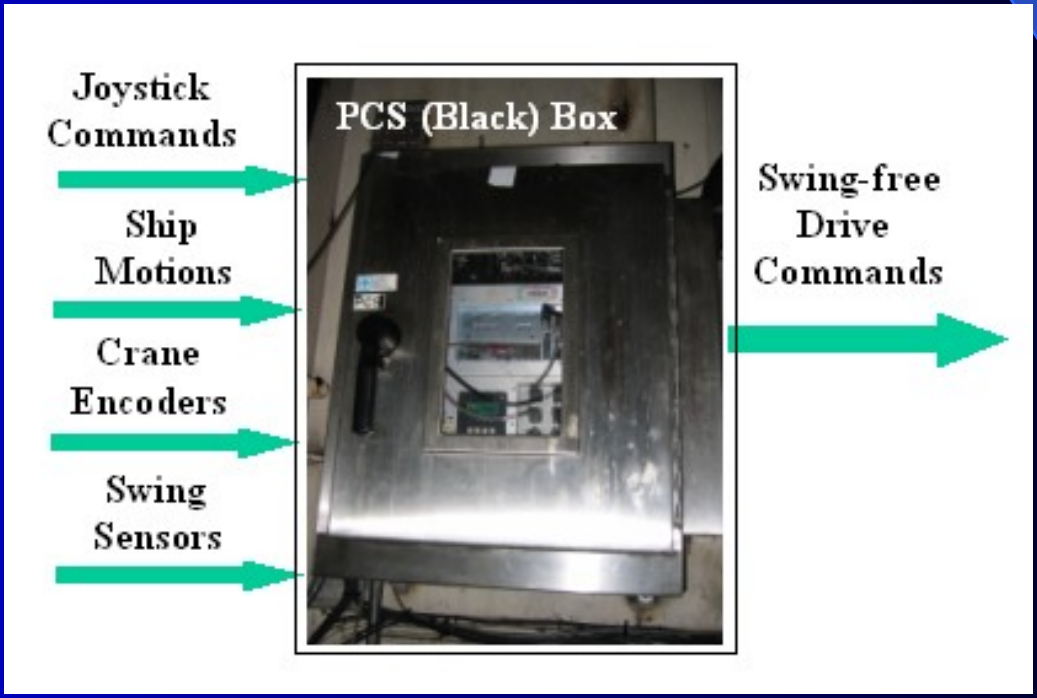






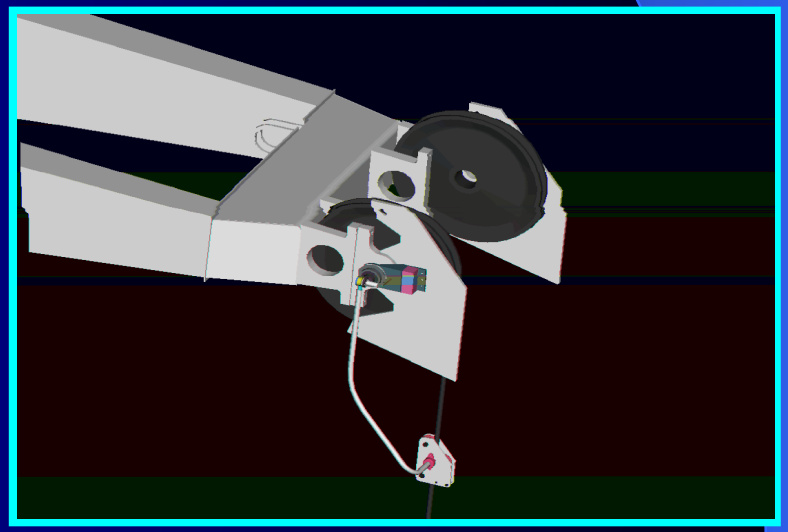
Control Systems

- Crane machinery controlled by an external unit, in addition to the crane manufacturer's devices
- Hardware-in-the-loop approach treating any external control unit as a "black box"



Sensory Systems

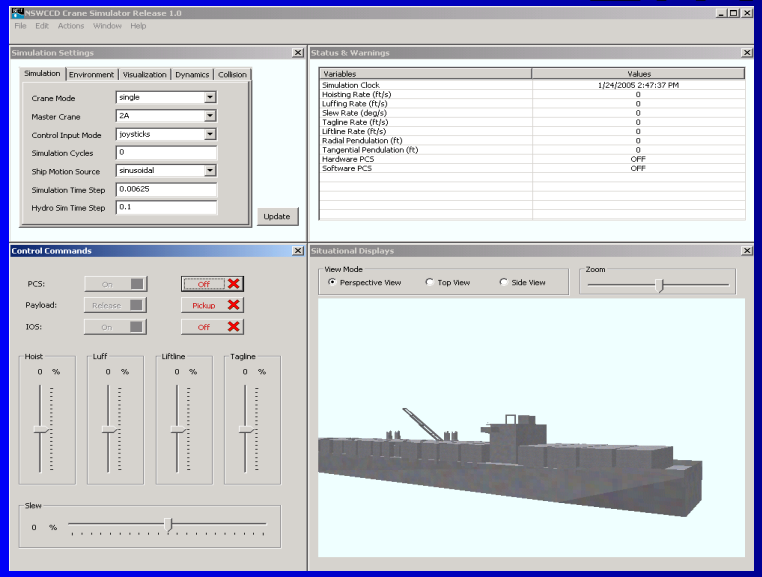
- GPS-aided Inertial Navigation System (INS) to sense six degrees-of-freedom ship motions
- Incremental and absolute encoders to measure crane boom and slew positions and speeds
- Swing sensors to estimate in-plane and out-of-plane payload pendulation angles

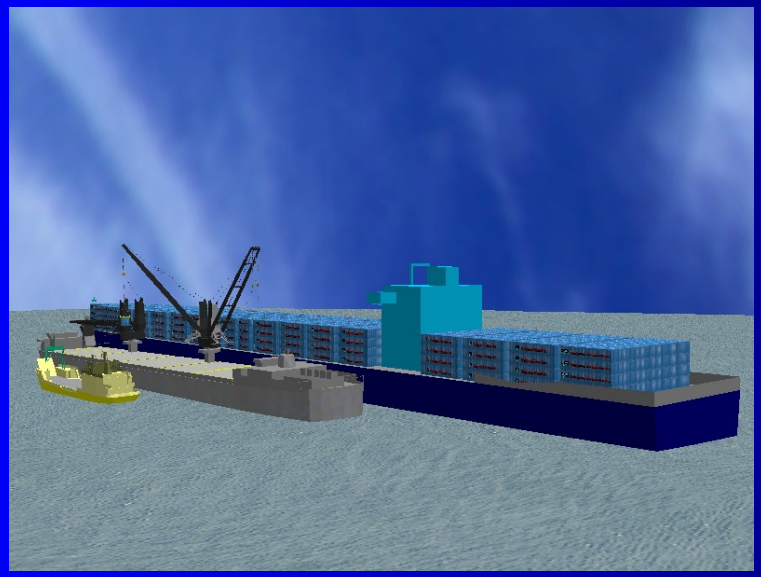


Visual and Audio Systems

- Visualization was implemented based on a cross platform C/C++ OpenGL API
- Visual display was provided to the crane operator via a 4-meter eLumens visual dome
- A second visual channel via a HMD is available for team scenario such as signalman training
- Efficient collision algorithm to detect possible contacts between moving bodies in real-time
- Audio cueing is generated based on winch actions and detected collisions

Integrated Virtual Environment





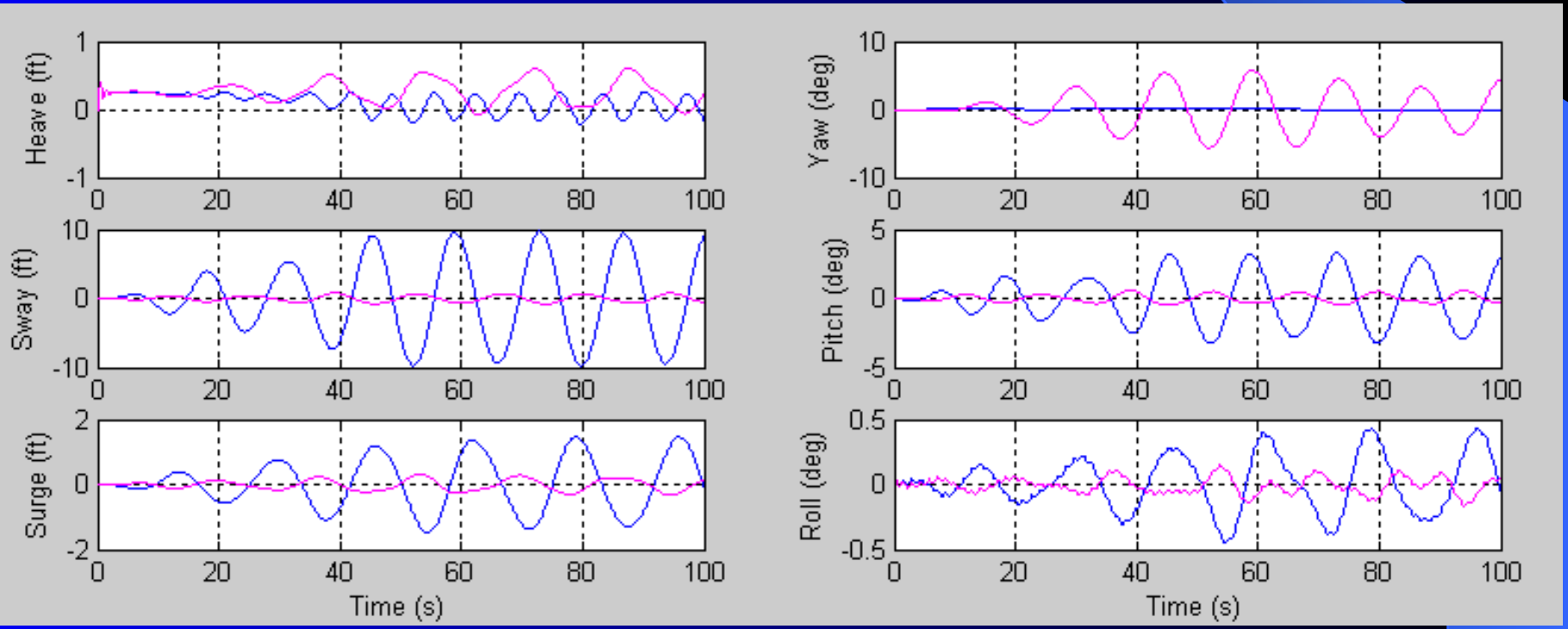
Control System Performance Evaluation

- Boom aligned with ship centerline and boom angle at about 25 degrees from horizontal
- Sinusoidal ship motions:
  - roll of 3 degrees at a period of 13.9 seconds
  - pitch of 0.5 degrees at a period of 16.7 seconds, and
  - heave of 5.7 feet at a period of 17.2 seconds
- Pendulation motion was resolved into the ship-fixed coordinate system of surge, sway, heave, pitch, roll, and yaw

Closed-loop PCS Performance

- No Joystick Inputs

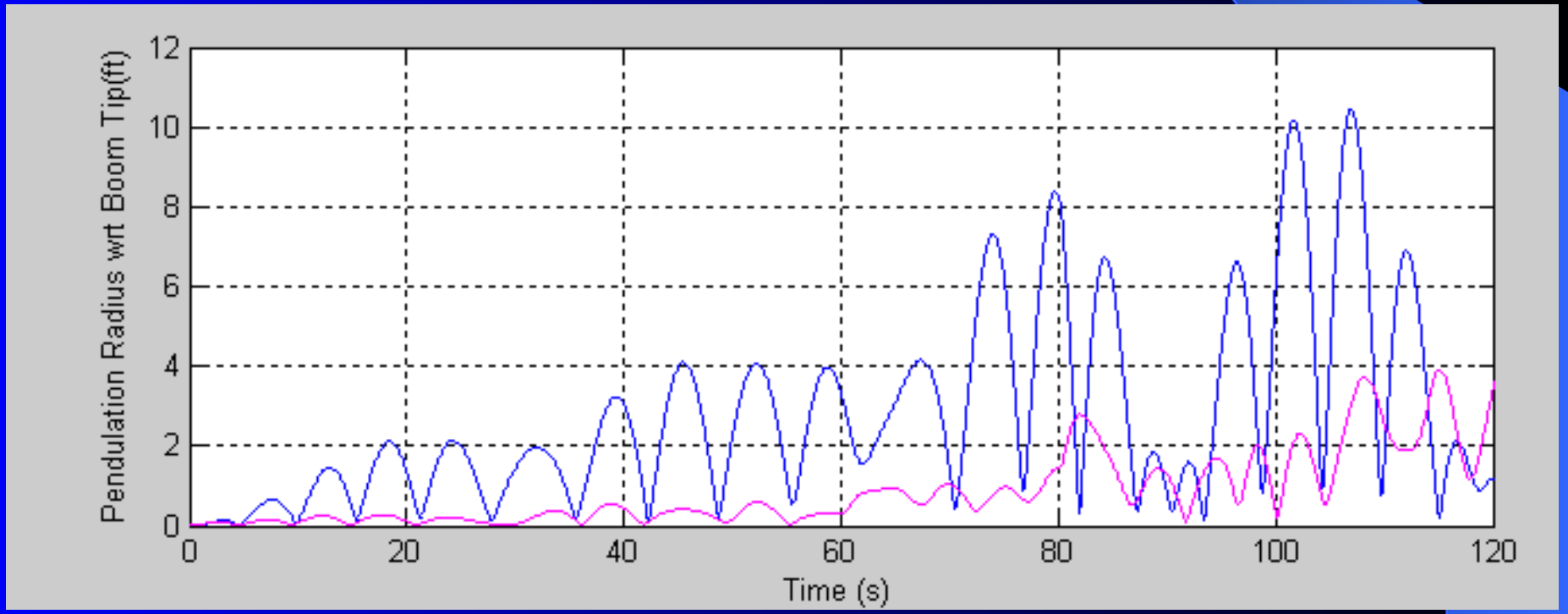
- The PCS enabled the testbed to significantly reduce the payload pendulation
- Introduced small yaw motion, i.e., some energy flows from translational to rotational modes



Closed-loop PCS Performance

- With Simulated Operator Input

- Driving with pre-recorded joystick inputs: boom-up, hoist-up, then slew about 90 degrees
- Plotted horizontal pendulation as observed vertically downwards from the boom tip

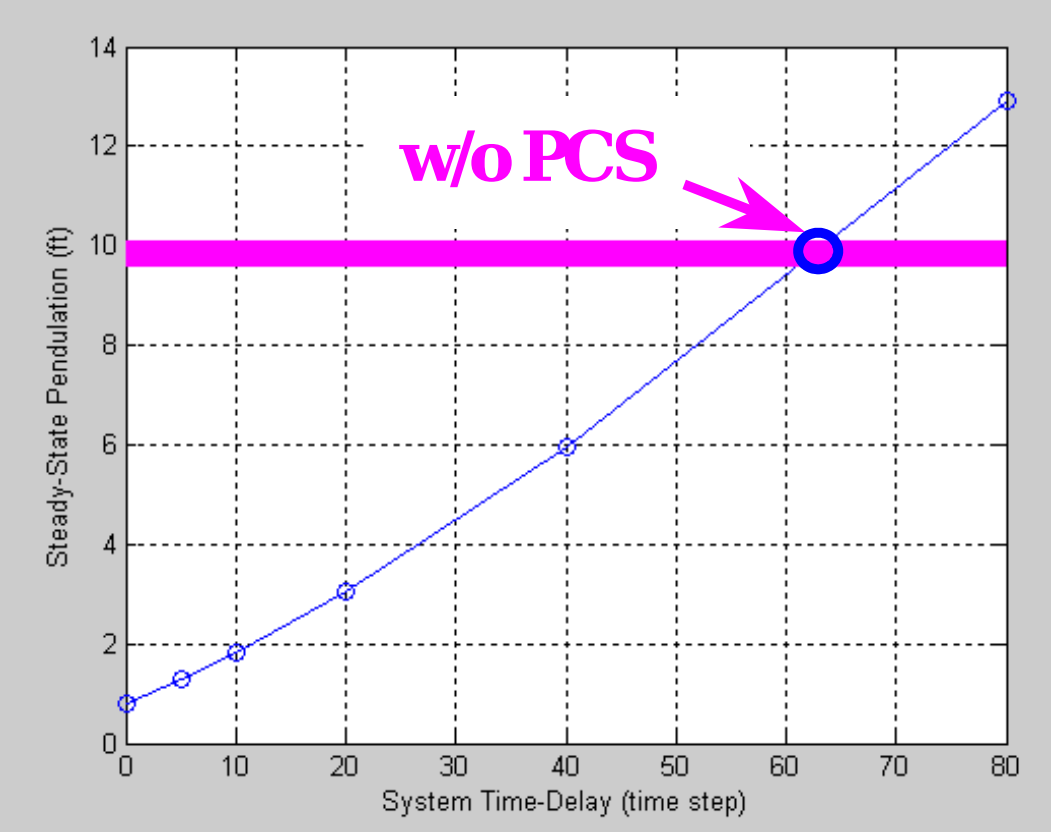


Engineering Design and Evaluation

- Testbed for engineering designs and evaluations, with the option of human-in-the-loop and/or hardware-in-the-loop
- Application scenarios:
  - Specify subsystem design parameters such as required sampling frequencies of encoders
  - Determine communication protocol for the integrated system such as maximum allowed system time-delay
  - Evaluate new designs of mooring lines or fenders and best configuration for deployment arrangement
  - Study utility of using commercial dynamic positioning systems in notional Seabasing support ships

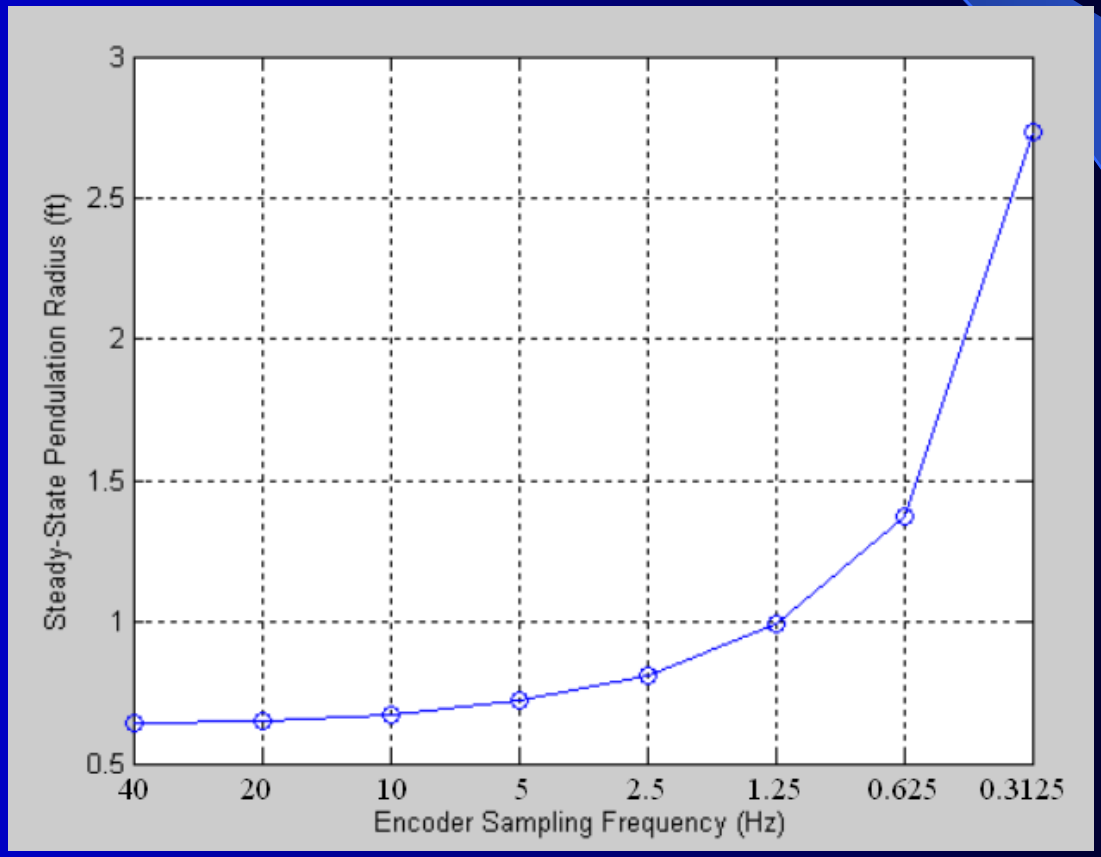
Impact of System Time-Delay

- Generally, the performance of a control system is expected to degrade with increasing time delay
- Using the testbed to find out an appropriate value



Impact of Encoder Sampling Frequency

- The more demanding the requirement, the higher the cost. It also limits the number of candidate subsystems that may be selected.



Summary and Discussions

- Physics-based, high fidelity M&S
- Real-time and fast time simulations
- Human-in-the-loop and hardware-in-the-loop
- Visual and audio cueing for quality virtual environment presence
- Open-architecture and object-oriented design
- Graphical user interface

Summary and Discussions

- An asset for exploration of concepts for skin-to-skin cargo transfers at sea while underway in sea states 4 or greater
- Engineering tool for specification and testing of subsystem performance and interfaces
- “Training” tool for introduction and evaluation of new technologies with human interaction
- “System of systems” approach - Flexible, modular, expandable, reusable, and interoperable
- Cost-effective and timely

Questions?